APPLICATION OF APEX FOR FORESTRY

A. Saleh, J. R. Williams, J. C. Wood, L. M. Hauck, W. H. Blackburn

ABSTRACT. *This study was conducted to determine if the Agricultural Policy/Environmental Extender (APEX) model could reasonably replicate the effects of silvicultural practices on streamflow and loading of sediments and nutrients. APEX was modified to enhance factors associated with forestry conditions such as rainfall interception by canopy, litter, subsurface flow, nutrient movement, and routing enrichment ratios. Historical data from the Alto watershed forestry project in east Texas were used to calibrate and test APEX. The historical data included measured flow, sediment losses, and nutrient (NO_3−N, organic N, total N, PO_4−P, organic P, and total P) losses from nine small (2.6 to 2.7 ha) watersheds, with three replicates of each of the following treatments: (1) clearing, shearing, windrowing, and burning (SHR); (2) clearcutting, roller chopping, and burning (CHP); and (3) undisturbed control watersheds (CON). In addition, the modified APEX model was applied to two of the watersheds to demonstrate its capabilities in simulating an important sediment source (roads) and an effective best management practice (streamside management zones, or SMZs).*

The simulated and measured storm runoff, peak flow rates, and average annual sediment and nutrient losses were in reasonable agreement. Simulated storm runoff per mm of rainfall increased six times for SHR and five times for CHP watersheds during the first post−treatment year as compared to CON watersheds. Consequently, the sediment concentration increased about 13 times for SHR and doubled for CHP watersheds. The nutrient loading also increased during the first post−treatment year in SHR and CHP watersheds. However, storm runoff and sediment and nutrient losses were reduced during the second post−treatment year due to rapid vegetation growth. Storm runoff, along with sediment and nutrient losses from both SHR and CHP watersheds, approached those of CON watersheds during the fourth and fifth post−season years. In general, the modified APEX performance was reasonable considering that forestry losses are generally one or two orders of magnitude lower than agricultural losses. Further APEX simulations demonstrated that SMZs decreased the average annual runoff and sediment loss, while forest roads along with greater slope increased runoff and sediment loss from forested land.

Keywords. *Flow, Forestry, Models, Nutrients, Sediment, Water quality.*

The amount of nutrients leaving a forested watershed may be subject to an increase due to silvicultural practices such as timber harvesting and residue removal or treatment (Moore and Norris, 1974). Bormann et al. (1968) and Likens et al. (1970) are among the first researchers who reported elevated stream nutrient concentrations following forest clearcutting. Pierce et al. (1972), Hornbeck (1975), Martin and Pierce (1980), and Feller and Kimmins (1984) reported significant increases in stream nutrients the first three years following clearcut harvesting in the White Mountains of New Hampshire and southwest British Columbia. Blackburn and Wood (1990) and Blackburn et al. (1986) determined storm flow water quality as affected by (1) clearcutting, shearing, windrowing, and burning and (2) clearcutting, roller chopping, and burning in a study conducted from 1980 to 1985 in east Texas. They reported that although nutrient losses from all treatments were small, shearing and windrowing had the greatest impact on nutrient losses. They also concluded that nutrient losses and concentrations were greatest during the first year following harvesting and site preparation.

Field studies in forestry, besides being relatively expensive and time intensive, depend on weather patterns and other environmental factors. For instance, timber crops usually take about 25 years to mature. Therefore, it would take many years (e.g., 25 years) to complete a research study regarding the effect of timber harvesting on water quality. Hydrologic, water quality−based models that have been tested successfully with measured data provide a faster and easier way to evaluate the effect of silvicultural practices on water quality at the watershed level. There are several benefits of modeling compared to watershed experiments. Modeling can represent the mean conditions of the simulated area, it can explore the affect of a larger spectrum of possible sequences of events, and it is not influenced by environmental events such as meteorological extremes that can affect to a great degree the results of short−term watershed experiments. However, while most computer simulation models regarding forestry

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have been developed to estimate flow and sediment losses (Elliot et al., 2000; Lewis, 2000; Elliot and Hall, 1997), limited work has been done to predict nutrient losses from forestlands. Therefore, this study was conducted to: (1) modify the Agricultural Policy/Environmental Extender (APEX) (Williams et al., 2000) to improve predictions of flow, sediment, herbicides, and nutrient losses from silvicultural lands; (2) use the historical data reported by Blackburn et al. (1986) to test the modified APEX model; and (3) evaluate selected BMPs such as filter strips (SMZs) and road construction using the modified APEX.

Methods and Materials

Model Description

APEX (Williams et al., 1995; Williams et al., 2000) was developed for use in whole farm and small watershed management. The model was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, plant competition, weather, and pests. Management capabilities include irrigation, drainage, furrow diking, filter strips (stream management zones, or SMZs), terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, herbicide application, grazing, and tillage. In addition to these farm management functions, APEX can be used in evaluating the effects of alternative global climate and/or carbon dioxide changes, designing environmentally safe and economically efficient landfill sites, designing biomass production systems for energy, and other spin−off applications. The model operates on a daily time step and is capable of simulating hundreds of years, if necessary. The landscape may be subdivided into fields, soil types, landscape positions, or any other desirable configuration, and the model may be run at either a field or watershed scale.

The individual field simulation component of APEX is taken from the Environmental Policy Integrated Climate (EPIC) model. The EPIC model was developed in the early 1980s to assess the effect of erosion on productivity (Williams, 1990). Various components from CREAMS (Knisel, 1980) and SWRRB (Williams et al., 1985) were used in developing EPIC. The GLEAMS herbicide component was added later (Leonard et al., 1987). The drainage area considered by EPIC is generally a field−size area, up to 100 ha, in which weather, soils, and management systems are assumed to be homogeneous. The major components in EPIC are weather, hydrology, erosion, sedimentation, nutrient cycling, herbicide fate, plant growth, soil temperature, tillage, economics, and plant environment control. Although EPIC operates on a daily time step, the optional Green and Ampt infiltration equation simulates rainfall excess rates at a shorter time interval (0.1 h). The model offers options for simulating several other processes, including five evapotranspiration equations, six erosion/sediment yield equations, and two peak runoff rate equations. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, herbicides, and sediment losses. The management components include crop rotations, tillage operations, irrigation scheduling, drainage, furrow diking, liming, grazing, tree pruning, thinning and harvest, manure handling, and nutrient and herbicide application rates and timing.

The APEX model was developed to extend the EPIC model capabilities to whole farms and small watersheds. APEX components include the routing of surface water, sediment, nutrients, herbicides, and groundwater. A watershed can be subdivided as needed to ensure that each subarea is relatively homogeneous in terms of soil, land use, management, etc. The routing mechanisms provide for evaluation of interactions between subareas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of nitrogen (nitrate and organic), phosphorus (soluble and organic), and herbicide concentrations may be predicted for each subarea and at the watershed outlet. Commercial fertilizer or manure may be applied at any rate and depth on specified dates or automatically. The GLEAMS herbicide component in APEX is used to estimate herbicide fate considering runoff, leaching, sediment transport, and decay. Because of routing through subareas in APEX, there is no limit on watershed size. However, a practical limit may be about 2,500 km^2. This limit is because of the detailed crop management system of APEX and because daily rainfall is distributed uniformly over the entire watershed. APEX has its own databases for weather simulation, soils, crops, tillage, fertilizer, and herbicides for a major part of the U.S., and convenient interfaces are supplied for assembling inputs and interpreting outputs.

Model Modifications

The modified components in APEX used to describe the hydrology under forest conditions are shown in figure 1.

Rainfall Interception by Canopy

Rainfall interception by the plant canopy can be estimated with the equation (Chow, 1964):

$$RFI = RIMX\,(1 - e^{(-bi\sqrt{TAGP \times SMLA})})\ ;\ RFI < RF \quad (1)$$

where *RFI* is the intercepted rainfall (mm), *RIMX* is the maximum possible intercepted rainfall for an event (mm), *RF* is the rainfall for the event (mm), *TAGP* is the aboveground plant material (t/ha), *SMLA* is the leaf area index of the plant stand, and *bi* is a constant set to a value of 0.1 by considering boundary values of *TAGP* and *SMLA* (a crop with *TAGP* = 5t/ha and *SMLA* = 3 gives *RFI / RIMX* = 0.78; a forest with

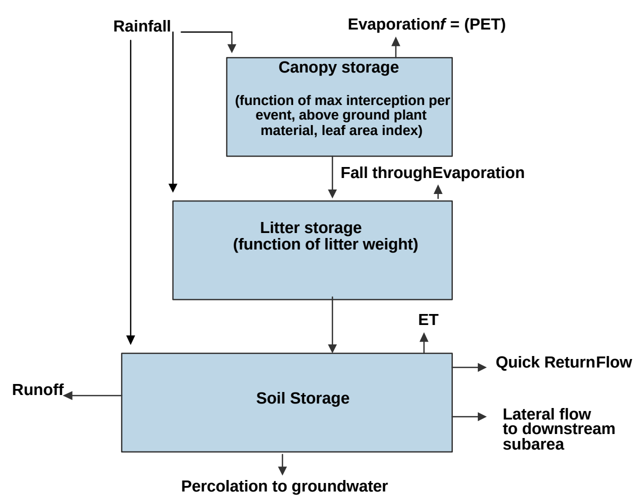

Figure 1. Modification of APEX for forestry conditions.

TAGP = 100 and *SMLA* = 3 gives *RFI / RIMX* = 1.0). Equation 1 was constructed for general operation on a variety of land uses including cropland, pastureland, range, and forestland. Intercepted rainfall is allowed to evaporate at the potential evapotranspiration (PET) rate. If PET exceeds *RFI*, then the excess potential is applied to evaporation from litter. If *RFI* exceeds PET, then the excess rainfall is added to water stored in litter.

Surface Litter Water Balance

Potential soil surface evaporation is estimated with the equation (Williams et al., 2000):

$$ES = EO \times e^{(-0.4 \times SMLA)} \tag{2}$$

where *ES* is the potential soil surface evaporation (mm), and *EO* is the excess PET (mm) after evaporating intercepted rainfall. *ES* is applied to snow cover, water in litter, and soil water, in that order. The mass balance equation for water in litter (Williams et al., 2000) is:

$$SWLT = SWLTO + RF - RFI - Q - EV - PRK \tag{3}$$

where *SWLT* and *SWLTO* are the water contents in litter at the end and the start of the day, *Q* is the surface runoff, *EV* is the actual evaporation from the litter, and *PRK* is the percolation through the litter (all in mm):

$$EV = ESS \qquad WLT > ES \tag{4}$$

$$EV = SWLT \qquad SWLT < ES \tag{5}$$

$$PRK = SWLT - SLMX \qquad SWLT > SLMX \tag{6}$$

$$PRK = 0 \qquad SWLT < SLMX \tag{7}$$

where *SLMX* is the maximum water storage in the litter after percolation (mm). *SLMX* is estimated with the equation:

$$SLMX = bl \times RSD \tag{8}$$

where *bl* is a coefficient with an arbitrary value of 0.5, and *RSD* is the litter or surface residue cover (t/ha). The value of *b1* set to 0.5 implies 5 mm of storage for a residue cover of 10 t/ha, which is comparable to maximum canopy interception (*RIMX*).

Quick Return Flow

The original APEX subsurface flow model included vertical and horizontal components (Williams et al., 2000). The vertical or percolation component flowed to groundwater storage and was subject to deep percolation from the system and return flow. The entire horizontal component flowed to the next downstream subarea beneath the soil surface. This assumption may be valid for small areas (landscape positions along a hillside), but it is not appropriate for larger, more complex subareas. Thus, in the new APEX version, part of the horizontal flow enters the channel within the subarea (quick return flow) and part flows to the next downstream subarea, as in the original model. A quick return flow component was developed and added to the original model as part of the work reported here. The quick return flow is added to the channel flow from the subarea instead of being added to the downstream subarea's soil water (fig. 1). The new model partitions flows as follows:

$$O_i + Oh_i = (St_i - FC_i) \times X3 \qquad St_i > FC_i \tag{9}$$

where $X3 = 1 - e^{[(-24/TT_i) + (-24/TTH_i)]}$ and O_i is the percolation rate (mm/d), Oh_i is the lateral subsurface flow rate (mm/d), St_i is the soil water content in the root zone, FC_i is field capacity (mm), TT_i is the vertical travel time (h), TTH_i is the horizontal travel time (h), and subscript *i* is the soil layer number. The vertical travel time is computed with the equation:

$$TT_i = \frac{PO_i - FC_i}{SC_i} \tag{10}$$

where PO_i is the soil porosity (mm), and SC_i is the saturated conductivity (mm/h). The horizontal travel time is computed with the equation:

$$TTH_i = \frac{HST_i}{HCL_i} \tag{11}$$

where HST_i is the soil water storage (mm), and HCL_i is the horizontal saturated flow rate (mm/h). The horizontal saturated flow rate is computed with the equation:

$$HCL_i = SC_i \times STP_i \tag{12}$$

where STP_i is the land slope (m/m). The horizontal storage (St_i) is computed with the equation:

$$St_i = \frac{(PO_i - FC_i)\, 0.5 \times SPLG}{DZ} \tag{13}$$

where *SPLG* is the land slope length (m), and *DZ* is the soil layer thickness (m). Only half the slope length is considered because the travel time is computed from the centroid of the slope to the outlet. Taking the ratio of Oh_i / O_i and substituting the resulting Oh_i into equation 9 leads to the equation:

$$O_i + (O_i \times X2 - X1) = (ST_i - FC_i) \times X3 \tag{14}$$

where

$$X1 = 1 - e^{\left(\frac{-24}{TT_i}\right)}$$

$$X2 = 1 - e^{\left(\frac{-24}{TTH_i}\right)}$$

Solving for O_i gives the final percolation equation:

$$O_i = \frac{(ST_i - FC_i) \times X3}{1 + \frac{X2}{X1}} \tag{15}$$

Lateral flow is partitioned between quick return flow and subsurface flow to the adjacent downstream subarea using the following equations (Williams et al., 2000):

$$SSF_i = \frac{0.001 \times (ST_i - FC_i - O_i) \times SPLG_i}{RCHL} \tag{16}$$

$$QRF_i = ST_i - FC_i - O_i - SSF_i \tag{17}$$

where QRF_i is quick return flow rate (mm/d), SSF_i is the subsurface flow rate (mm/d), and *RCHL* is the reach channel length (km). As the ratio of *SPLG / RCHL* approaches 1.0 (very small area), all of the subsurface flow remains below ground and enters the adjacent subarea's soil water storage. Conversely, as the ratio approaches 0.0, all of the subsurface flow resurfaces as quick return flow.

Soluble P Upward Movement by Evaporation

Previously, APEX simulated the upward movement of NO_3−N, but not soluble phosphorus, by water evaporating from the soil. Although soluble P transport by water in soil is much less than that of NO_3−N, we included the process in this work. Upward movement of soluble P is simulated with the equation used for leaching P (Williams et al., 2000):

$$EVP = \sum\left(\frac{AP_i \times SEV_i}{WT_i}\right);\ i = 2, M \qquad (18)$$

where EVP is the soluble P moved into the top soil layer by water evaporating from the lower layer (kg/d), AP_i is the soluble P content (kg/ha), SEV_i is the water evaporation rate (mm/d), WT_i is the soil weight (t/ha), i is the soil layer number, and M is the maximum number of soil layers.

New Nutrient Enrichment Ratio Parameters

Previously, the user could choose to compute nutrient enrichment ratios with equations from EPIC or GLEAMS. In either case, the same enrichment ratio was applied to organic N and P. Both approaches estimate enrichment ratio as a nonlinear function of sediment concentration. Although enrichment ratios were developed for use on small upland watersheds, they have been used in APEX to route organic nutrients through channels and floodplains. The EPIC method gave satisfactory results for the upland areas in this study. However, neither approach performed well in routing through channels and floodplains, probably because of the extremely low sediment concentrations encountered in forest settings. This deficiency led to the development of new parameters to estimate routing enrichment ratios for N and P separately. The new equations are:

$$ERTN = \frac{0.593}{CIN^{(0.176)}} \qquad (19)$$

$$ERTP = \frac{0.125}{CIN^{(0.301)}} \qquad (20)$$

where $ERTN$ and $ERTP$ are the enrichment ratios for N and P, and CIN is the sediment concentration of the inflow to the reach (t/m^3). The EPIC parameters are variable depending on sediment delivery ratio and assumptions about boundary conditions, but the GLEAMS parameters are given in the equation:

$$ERT = \frac{0.78}{CIN^{(0.247)}} \qquad (21)$$

where ERT is the enrichment ratio for both N and P.

Partial Burning of Aboveground Plant Material

Previously, the APEX burn operation destroyed all aboveground plant material along with nitrogen. However,

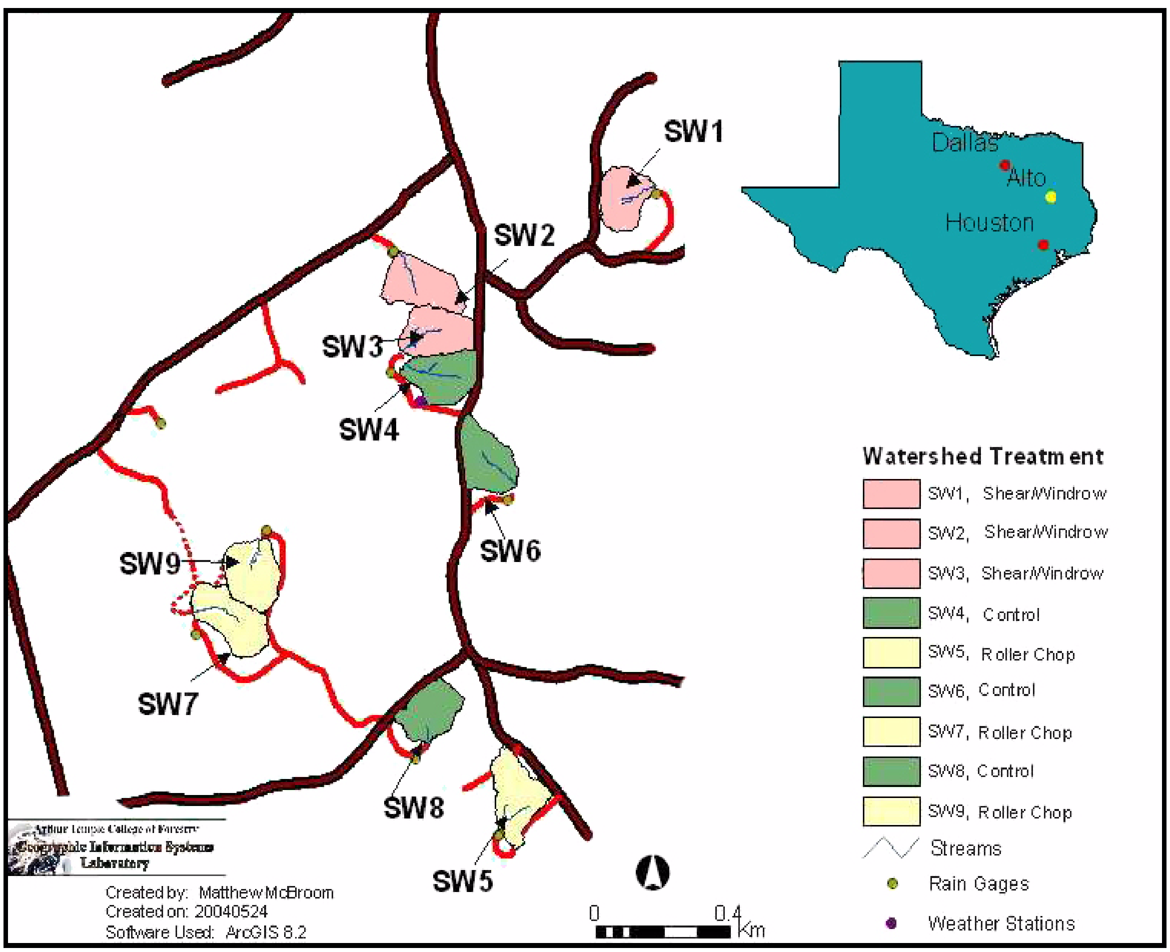

Figure 2. Alto watershed location in east Texas (from McBroom, 2004).

phosphorus was not affected by the burning operation. Since a forest fire does not completely destroy all plant material, the user now has the ability to set the fraction destroyed. The same fraction of N is lost, and as before, P is preserved. In addition, water stored in the litter is totally lost.

Test Sites

The majority of forestland in east Texas is managed primarily for pine sawtimber and pulpwood. Nine forested watersheds located in southwest Cherokee County in east Texas (USGS Cataloging Unit 12020001) were selected for this study (fig. 2). These watersheds ranged in size from 2.6 to 2.7 ha and were instrumented in 1979 to determine the effect of harvesting and mechanical site preparation on storm flow and water quality (Blackburn et al., 1986). The average slope was 9% among all watersheds. Vegetation cover in these watersheds predominantly consisted of short−leaf pine and pine−hardwood tree mixture. The area was previously managed under a selective cutting system, with the last harvest occurring in 1971 and 1972. Mean annual temperature is 19 °C with an average of 246 frost−free days. The annual average precipitation is about 1070 mm.

The Cuthbert and Kirvin series cover 78% of the soil surface of these watersheds (table 1). These soils are classified as clayey, mixed, thermic Typic Hapludults with a sandy loam A horizon (72% sand, 19% silt, and 9% clay) to a depth of 250 mm, and a clay textured B horizon. The remaining 22% of the soils are composed of three soil series (Lilbert, Tenaha, and Rentzel). These series are characterized by deep loamy fine sandy A horizons and Ultisoils (Steptoe, 1980).

Treatments

The nine watersheds were divided randomly into three groups, each containing relatively equal soil types (table 1) and geomorphic characteristics such as drainage density and circularity ratio (table 2). The following three treatments were randomly assigned to each group:

- Clearcutting followed by shearing, windrowing, and burning (SHR): these watersheds were harvested during the summer of 1980 and sheared with a V−blade, windrowed, and the windrows burned (watersheds 5, 7, and 9).
- Clearcutting followed by roller chopping and burning (CHP): these watersheds were harvested, roller chopped, and then broadcast burned (watersheds 1, 2, and 3).
- Undisturbed control (CON): these watersheds were left undisturbed as controls (watersheds 4, 6, and 8).

After site preparation, 58% of surface soil was exposed on the SHR watersheds, compared to only 15% of the CHP plots (Blackburn et al., 1986).

Table 1. Major soils and their characteristics in Alto watersheds.

Soil Series	Soil Type	Texture Sand (%)	Texture Silt (%)	Texture Clay (%)	OM (%)	Bulk Density (gm/cc)	Cover (%)
Cuthbert	Sandy loam	72	19	9	3.9	1.09	69
Kirvin	Sandy loam	72	18	10	3.9	1.10	9
Lilbert	Loamy sand	77	17	6	3.3	1.10	10
Tenaha	Loamy sand	81	12	7	3.3	1.10	2
Rentzel	Loamy sand	78	14	8	3.8	1.10	10

Monitoring Data

Runoff and peak discharge were measured at the outlet of each watershed with 0.91 m H−flumes equipped with FW−1 water level recorders. In addition, a Coshocton wheel sampler followed by a splitter was used to collect a 0.05% per storm composite water sample. Watersheds 2, 6, and 9 were equipped with Isco water pump samplers. Water samples were automatically collected at 20 min intervals with a floating intake nozzle in the approach section of the flume at these sites. Water samples were analyzed for suspended solids, nitrate (NO_3−N), ammonium (NH_4−N), total N, orthophosphate phosphorous (PO_4−P), and total phosphorus (TP) using Auto Analyzer II. The complete laboratory procedures for determination of these nutrients are described by Blackburn et al. (1986). A network of 14 standard and 2 recording rain gauges within the watersheds measured daily precipitation. The average measured monthly rainfall for the period 1980−1985 among all watersheds is shown in figure 3.

APEX Simulations

For APEX simulations, including enhancement for forestry, each watershed was delineated into two subareas (upland and floodplain) based on actual field conditions. The floodplain represents the SMZs including trees that were left along all stream channels for all treatments. Subdividing was necessary to simulate channel erosion and floodplain deposition. Cuthbert soil was dominant in the upland areas, and Rentzel soil was dominant in the SMZ areas within the watersheds. The average curve number for each watershed was obtained (table 3) based on the weighted average of each soil type's assigned curve number using the *National Engineering Handbook* (USDA−SCS, 1972). It was assumed that all trees were planted at the beginning of simulation (1948) and were cut in 1981 with the exception of the CON watersheds. The initial runoff curve numbers (CN2) were calculated based on the soil fractions for each watershed reported by Blackburn et al. (1986). The curve numbers were changed for the six harvested watersheds as treatments developed during 1980−1985 using the *National Engineering Handbook* (USDA−SCS, 1972). For example, in 1948 the average CN2 for SHR watersheds was 66 (table 3). After the trees were clearcut in September 1980, ground cover (weeds, grass, and brush) increased gradually. The disturbance caused by the shear and windrow operations was simulated by an offset disk operation in November 1980, and the CN2 was changed to 80. In February 1981, the windrows were burned, and the CN2 was increased to 85. New pine trees were planted during February 1981. During 1981, ground cover again increased gradually. In January of 1982, the CN2 was set at 78 to simulate the effect of pine and winter pasture

Table 2. Geomorphic characteristics of Alto watersheds.

Watershed	Treatment	Area (ha)	Slope (%)	Drainage Density	Circularity Ratio
1	SHR	2.61	11.0	8.35	0.89
2	SHR	2.58	17.4	8.56	0.74
3	SHR	2.64	13.1	15.77	0.85
4	CON	2.66	13.4	11.14	0.82
5	CHP	2.71	12.3	10.41	0.81
6	CON	2.66	10.3	9.49	0.78
7	CHP	2.74	7.7	10.55	0.72
8	CON	2.61	10.8	11.54	0.88
9	CHP	2.74	12.6	10.31	0.88

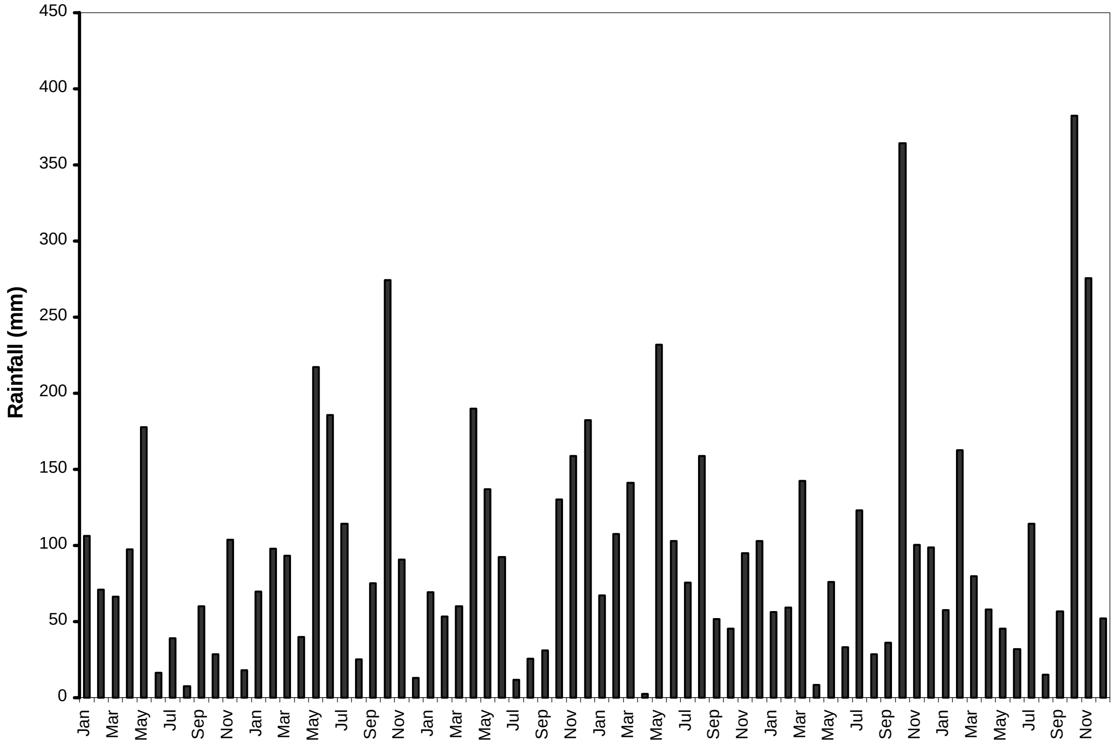

Figure 3. Average monthly rainfall among all watersheds.

Table 3. Simulated tillage operations and CN2 for different treatments (average of three watersheds per treatment).

Treatment	Year	Operation (and month)	CN2
SHR	1948	Planting pine (Jan.)	66
	1980	Clearcut and kill (Sept.)	75
		Offset disk (Nov.)	80
	1981	Burning (Feb.)	85
		Planting pine and winter pasture (Feb.)	85
	1982	No operation	78
	1983−85	No operation	73
CON	1948	Planting pine (Jan.)	73
CHP	1948	Planting pine (Jan.)	66
	1980	Clearcut and kill (Sept.)	75
		Tandem disk (Nov.)	80
	1981	Burning (Jan.)	80
		Planting winter pasture (Jan.)	80
		Planting pine (Feb.)	80
		Planting spring pasture (May)	80
	1982−85	No operation	75

planted in February 1981. Finally, the CN2 was changed to 73 in January 1983, where it remained for the duration of the simulation (December 1985).

Watershed 2 from Alto watersheds in east Texas was chosen to demonstrate the effectiveness of filter strips. The simulation began in 1948 when the pine trees were planted and continued through 1985. The trees in the upland area were harvested in the fall of 1979 using the shear and windrow method. Trees in the floodplain were not harvested so they could serve as an SMZ. The upland area was prepared and pine seedlings were transplanted early in 1980. Site preparation left bare disturbed soil exposed and extremely vulnerable to erosion. The effectiveness of the SMZs in controlling erosion was evaluated during the period 1980−1985. To establish a base condition, the first simulation assumed that all trees had been removed and there was no filter strip. Subsequent simulations were performed with the natural filter strip (10 m width on each side of stream) in place, assuming a range in filtering efficiency. To be effective, SMZs must maintain vegetative growth capable of filtering sediment from flowing water. In addition, runoff must flow through the filter and not occur in concentrated channel flow. APEX allows the user to specify the fraction of upland runoff that actually flows through the filter rather than in concentrated channel flow. Thus, the range in filtering efficiency was established by varying the filter flow fraction from 0.0 to 0.95.

Forest roads are a major contributor of sediment yield for many forested watersheds. To estimate the road contribution relative to other sources, simulations were performed on Alto watershed 4. Watershed 4 was not harvested during the period 1948−1985 and there were no roads in the watershed. To establish a base, the first simulation was performed with existing watershed conditions (no roads). Although the simulation extended from 1948 through 1985, only the period 1980−1985 was used in the analysis because this is the period when runoff, sediment yield, and nutrient concentrations were measured. Forest roads in the Alto area are about 6.1 m wide, vary in density from 1 to 3 km/km^2, and range in average road slope from 1% to 15% (M. McBroom, personal communication). The roads were simulated as a subarea in APEX covered with bare erodible soil, thus representing the worst possible forestry road condition.

Measure of Model Performance

The predicted and measured values were compared using standard deviation and the Nash and Sutcliffe (1970) equation as follows:

$$E = 1 - \frac{\sum_{i=1}^{n} (X_{mi} - X_{ci})^2}{\sum_{i=1}^{n} (X_{mi} - \overline{X}_m)^2} \qquad (22)$$

where E is the efficiency of the model, X_{mi} is the measured values, X_{ci} is the predicted values, and $\overline{X}_m$ is the average measured values. A value of E = 1.0 indicates a perfect match model. E is similar to a correlation coefficient obtained from linear regression; however, E compares the measured values to the 1:1 line of measured equals predicted (perfect fit) rather than to the best−fit regression line.

Results and Discussion

General Comparison

During the simulation period (1980−1985), the number of simulated rainfall events with runoff per watershed varied from 35 at watershed 8 to 108 at watershed 2. The majority of these storms occurred during the spring and fall seasons (fig. 3).

Tables 4 and 5 show that the simulated and measured average runoff, along with sediment and nutrient losses per storm event, were close. In addition, figures 4 through 11 show a similar trend between measured and predicted flow and sediment and nutrient losses. As expected, there were errors in observational data recorded for the watershed as well as in the model predictions. For example, in some cases runoff was recorded with no accompanying rainfall.

In forested watersheds such as Alto, the level of sediment and nutrient losses was relatively small. Sediment and nutrients are expressed in kg/ha and g/ha, respectively, as contrasted with t/ha and kg/ha in agricultural watersheds. Thus, any small error in magnitude can result in a large percentage error, which ultimately leads to lower model efficiencies. Note that the means and standard deviations of the simulated and observed data generally compare closely. For example, in spite of low E values for watersheds 2 through 9, the average simulated and measured sediment loss per storm event were very close (table 4).

The modified APEX model was able to reasonably simulate a variety of responses to forest conditions ranging from a mature forest, to harvested, site−prepared (shear and windrow and chopped), planted, and finally regrowth forest. The model was not calibrated during this study. Parameter values were assigned using previously developed tables, boundary considerations, and from previous experience.

Storm Runoff

A reasonable ($E \geq 0.74$) pattern was found between the simulated and observed storm runoff on all watersheds (table 4 and fig. 4). Similar to field measurements, the predicted average runoff per storm event ranged from 2.03 mm for watershed 4 to 6.08 mm for watershed 2 and averaged 4.47 mm for all nine watersheds, which is close to what was measured during field experiments (4.76 mm). During the first post−treatment year (1981), the SHR and CHP watersheds produced 163 and 108 mm of predicted runoff, respectively, likely due to the surface disturbance, as compared to 17 mm from CON watersheds (table 6). Runoff as a percentage of annual precipitation averaged 12.6%, 8.4%, and 1.3% for the SHR, CHP, and CON watersheds, respectively. The rainfall amount shown in table 6 is an average of two gauges. Similar to what was observed during the field study, there was about six times more simulated storm runoff for SHR watersheds and five times more for CHP watersheds as compared to the CON watersheds in 1981. In addition, higher peak runoff rates were obtained from model simulation for SHR (7.1 mm/h) and CHP

Table 4. Measured and simulated average storm runoff, peak flow rates, and sediment loss for three treatments.

	Treatment and Watershed Number								
	SHR			CON			CHP		
	1	2	3	4	6	8	5	7	9
Number of storm events	92	108	93	59	64	35	60	70	94
Average storm runoff (mm)									
Measured	5.28	6.48	3.91	2.64	5.84	3.65	4.31	5.04	6.05
Simulated	5.58	6.08	4.44	2.03	4.09	2.88	4.98	5.37	4.79
Standard deviation									
Measured	11.28	12.83	8.85	7.10	12.30	9.78	9.19	10.90	11.56
Simulated	12.20	11.32	9.72	7.45	11.33	8.91	9.96	11.60	10.49
Model efficiency (E)	0.85	0.74	0.85	0.88	0.84	0.85	0.75	0.87	0.74
Peak discharge rate (mm/h)									
Measured	4.08	4.54	3.14	1.19	2.72	2.29	1.59	2.16	2.59
Simulated	5.11	4.77	4.08	1.52	3.53	2.11	2.07	2.22	2.00
Standard deviation									
Measured	8.45	9.23	6.47	3.88	7.00	7.07	4.35	5.64	6.69
Simulated	13.14	8.18	8.61	5.16	9.19	5.96	4.26	4.87	4.41
Model efficiency (E)	0.44	0.30	0.52	0.70	0.74	0.39	0.19	−0.05	0.65
Sediment (kg/ha)									
Measured	27.03	39.86	50.05	6.83	11.67	5.17	2.13	3.48	6.69
Simulated	26.05	34.76	55.98	7.49	11.31	4.91	2.22	4.25	6.93
Standard deviation									
Measured	77.93	120.29	140.79	32.79	44.07	15.98	7.81	15.71	35.03
Simulated	73.99	105.86	196.14	34.52	41.37	17.62	5.85	12.70	22.17
Model efficiency (E)	0.78	0.26	0.37	0.12	0.33	0.27	−0.99	0.29	−1.4

(3.4 mm/h) watersheds than for CON (2.9 mm/h) watersheds. During the field study, greater storm runoff and sediment and nutrient losses occurred on SHR watersheds as compared to CHP watersheds, which can be attributed to factors such as higher loss of plant and litter material, greater soil exposure to raindrop impact, and greater soil surface compaction by heavy shearing and windrowing equipment in SHR watersheds. The CN2 was set at the beginning of simulation according to soil class and soil surface cover for all watersheds. However, CN2 was modified according to the soil surface conditions throughout the simulation for SHR and CHP watersheds (table 3).

During the second post−treatment season (1982), the average measured precipitation was more evenly distributed throughout the year and was about 155 mm lower than in 1981. The lower precipitation along with simulation of surface revegetation (as pasture) for CHP and SHR treatments resulted in significant decrease in storm runoff during 1982 from the previous year for all treatments (table 6 and fig. 4). Storm runoff from SHR (56 mm) and CHP (17 mm) watersheds was still higher than that of the CON (2 mm). Simulated runoff expressed as a percentage of annual precipitation was 5%, 2%, and <1% for the SHR, CHP, and CON watersheds, respectively. The highest peak flow rate for the year was 2.4 mm/h on SHR watersheds. Although lack of data makes it difficult to compare simulated storm runoff between 1981 and 1982 post−treatment seasons, it appears that during the second post−treatment year (1982), the

Table 5. Measured and simulated average nutrients (including NO_3−N, organic N, PO_4−P, organic P, NO_3−N + organic N, and total P) losses for three treatments.

	Treatment and Watershed Number								
	SHR			CON			CHP		
	1	2	3	4	6	8	5	7	9
Number of Storm Events	92	108	93	59	64	35	60	70	94
NO_3−N (g/ha)									
Measured	7.67	13.50	5.39	4.81	7.24	7.13	5.10	4.24	9.73
Simulated	13.17	14.06	13.00	3.71	6.24	4.87	8.04	8.43	7.89
Standard deviation									
Measured	18.97	37.48	14.21	19.18	19.05	30.40	13.08	10.51	42.66
Simulated	28.67	29.34	28.46	11.49	17.80	12.93	17.27	19.69	18.64
Model efficiency (*E*)	0.41	−0.99	0.14	0.40	0.80	−1.42	0.03	0.11	−2.01
Organic N (g/ha)									
Measured	58.98	77.26	47.22	36.91	45.34	27.47	26.55	30.63	51.37
Simulated	61.02	80.45	102.71	33.83	46.50	25.37	13.24	24.83	39.91
Standard deviation									
Measured	130.65	185.64	119.71	153.92	106.06	82.27	57.15	69.60	120.61
Simulated	137.01	179.86	266.03	136.10	142.10	79.11	28.33	64.52	112.36
Model efficiency (*E*)	0.75	0.34	0.44	0.83	0.72	0.64	−0.65	0.75	0.68
PO_4−P (g/ha)									
Measured	0.56	0.97	0.42	0.20	0.49	0.22	0.24	0.30	0.57
Simulated	1.00	0.93	0.93	0.09	0.19	0.14	0.14	0.13	0.21
Standard deviation									
Measured	1.75	2.65	1.32	0.75	1.50	0.80	0.60	0.82	1.83
Simulated	4.32	4.12	4.09	0.51	0.92	0.60	0.48	0.46	0.62
Model efficiency (*E*)	0.16	0.08	0.25	−1.58	−1.38	−1.25	−1.54	−2.58	−6.59
Organic P (g/ha)									
Measured	4.31	7.62	3.77	1.97	3.19	1.97	1.81	1.66	2.93
Simulated	4.56	5.98	6.98	2.63	3.84	2.09	1.45	2.95	4.74
Standard deviation									
Measured	11.55	23.41	10.68	6.32	8.15	5.23	6.17	3.53	8.84
Simulated	10.24	13.02	17.57	10.76	12.00	6.60	3.31	8.29	14.39
Model efficiency (*E*)	0.60	0.56	0.43	0.49	0.63	0.63	−1.05	0.41	0.64
Organic N + NO_3−N (g/ha)									
Measured	66.37	90.76	52.61	41.72	52.58	34.60	31.65	34.87	61.10
Simulated	74.19	94.51	115.71	37.54	52.74	30.24	21.28	33.26	47.80
Standard deviation									
Measured	146.18	209.18	131.50	171.88	122.19	110.89	66.07	89.67	159.57
Simulated	163.11	205.82	290.90	147.53	159.56	91.94	43.96	104.79	128.93
Model efficiency (*E*)	0.77	0.32	0.42	0.84	0.77	0.58	0.09	0.77	0.56
Total P (g/ha)									
Measured	4.87	8.59	4.19	2.17	3.68	2.19	2.05	1.96	3.50
Simulated	5.56	6.91	7.91	2.72	4.03	2.23	1.59	3.08	4.95
Standard deviation									
Measured	15.24	26.87	14.06	6.54	8.77	2.11	6.23	1.79	3.13
Simulated	13.56	16.05	20.59	11.07	12.56	2.22	3.40	3.08	4.95
Model efficiency (*E*)	0.82	0.14	0.50	0.55	0.67	0.63	−1.10	0.46	0.69

Table 6. Simulated average annual storm runoff, peak flow rates, and sediment loss for three treatments.

		Year					
Parameter	Treatment	1980 (pretreatment)	1981	1982	1983	1984	1985
Precipitation (mm)	SHR	791	1289	1156	1182	1136	1330
	CON	795	1304	1151	1187	1142	1330
	CHP	790	1296	1117	1170	1123	1330
Peak flow rate (mm/h)	SHR	1.4	7.1	2.4	3.5	2.7	9.0
	CON	3.8	2.9	0.1	0.4	0.4	8.0
	CHP	0.6	3.4	0.4	1.2	1.0	5.5
Storm runoff (mm)[a]	SHR	16.4 (2.07)	162.6 (12.6)	56.4 (4.8)	57.6 (4.9)	51.7 (4.6)	183.0 (13.8)
	CON	11.5 (1.45)	17.2 (1.3)	1.9 (0.2)	5.9 (0.5)	9.9 (0.9)	114.1 (8.6)
	CHP	14.1 (1.79)	108.7 (8.4)	17.0 (1.5)	43.6 (3.7)	25.8 (2.3)	165.4 (12.4)
Sediment (kg/ha)	SHR	21.9	2773.5	129.3	164.9	98.6	597.6
	Conc. (mg/L)	(136.4)	(1800.4)	(255.7)	(266.3)	(201.3)	(351.2)
	CON	25.3	42.0	1.0	6.1	13.3	537.5
	Conc. (mg/L)	(246.8)	(254.3)	(30.8)	(54.8)	(245.1)	(308.3)
	CHP	7.9	133.4	8.8	24.5	7.6	178.7
	Conc. (mg/L)	(59.1)	(124.9)	(39.6)	(48.7)	(31.1)	(98.3)

[a] Values in parentheses are storm runoff as a percentage of precipitation.

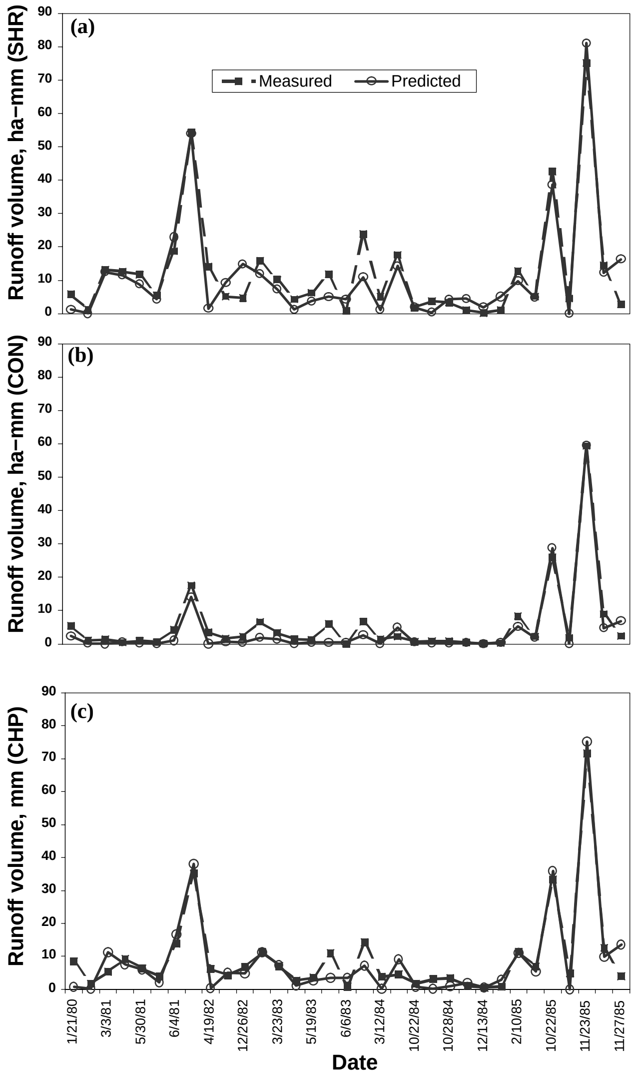

Figure 4. Simulated and measured storm runoff for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

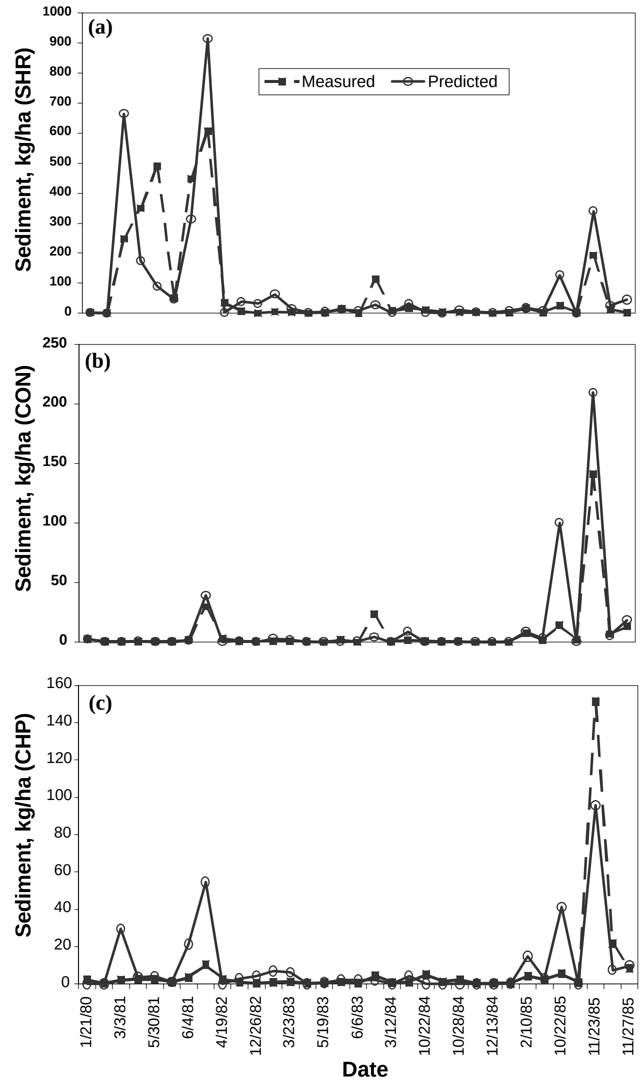

Figure 5. Simulated and measured sediment losses for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

differences in storm runoff between control and treatment watersheds as compared to 1981 were diminished (table 6 and fig. 4).

The simulated average annual storm runoff from CHP and SHR watersheds was similar (58 and 44 mm) but greater than that of the CON watersheds during the third post−treatment year (1983). Simulated storm runoff as a percentage of precipitation was 5%, 4%, and <1% for the SHR, CHP, and CON watersheds, respectively. The simulated average annual storm runoff decreased for SHR and CHP watersheds during the fourth post−treatment year (1984). However, runoff was still higher for SHR (52 mm) and CHP (26 mm) watersheds than for CON watersheds (10 mm).

The SHR and CHP watersheds continued to produce more simulated storm runoff than the CON watersheds during the last post−treatment year. Because of higher and more intense precipitation during 1985, the simulated storm runoff was higher for all treatments as compared to previous years. Simulated runoff as a percentage of annual precipitation was 14%, 12%, and 9% for SHR, CHP, and CON watersheds, respectively. In general, simulated storm runoff from SHR and CHP watersheds was higher than from the CON watersheds during the five post−treatment years. However, simulation of surface revegetation (as pasture) after the first post−treatment year narrowed the differences in treatment responses (fig. 4). Figure 4 shows the similarity of measured and predicted storm runoff trends.

SEDIMENTS

The simulated average annual sediment concentration during the first post−treatment year (1981) increased over 13 times for SHR watersheds and 2 times for CHP watersheds from the pretreatment year (1980) (table 6 and fig. 5). However, the 1981 average annual sediment concentration was nearly the same as the pretreatment year (1980) for the CON watersheds (table 6). The primary reasons for higher sediment loss from SHR compared to CHP watersheds are the amount of exposed surface cover and the disruption of soil surface caused by these treatments. During the field study, it was reported that after site preparation, the soil exposure on the CHP watersheds was about one−third of that of the SHR watersheds (Blackburn et al., 1986).

During the second post−treatment year (1982), sediment concentration and losses were considerably lower than in 1981. The average annual sediment concentration was over seven times lower for SHR and three times lower for CHP watersheds, as compared to the previous year. Simulated sediment concentration was also lower for CON watersheds (over eight times) during 1982. The large reduction in simulated sediment concentration during 1982 can be attributed to the lower precipitation recorded that year, in addition to the revegetation (as pasture) simulation of treated watershed during the year.

Similar patterns in simulated sediment concentration and losses to that of 1982 were obtained for 1983 and 1984. However, during 1985, the simulated annual sediment concentration and losses increased for all treatments (table 6) due to higher rainfall amounts.

Figure 5 shows the similarity of trends in measured and predicted sediment losses from all watersheds. As the simulated revegetation (pasture) progressed over the second, third, and fourth post−treatment years, simulated sediment

Table 7. Simulated average annual nutrients (including NO_3−N, organic N, PO_4−P, organic P, NO_3−N + organic N, and total P) losses for three treatments.

Parameter	Treatment	Year: 1980 (pretreatment)	1981	1982	1983	1984	1985
NO_3−N (g/ha)	SHR	74.0	562.9	240.8	78.6	68.6	288.1
	Conc. (mg/L)	(0.5)	(0.35)	(0.61)	(0.14)	(0.13)	(0.16)
	CON	17.1	32.1	5.6	11.4	20.2	264.8
	Conc. (mg/L)	(0.16)	(0.21)	(0.57)	(0.37)	(0.26)	(0.15)
	CHP	90.7	151.1	22.3	52.0	37.3	251.5
	Conc. (mg/L)	(0.64)	(0.2)	(0.15)	(0.12)	(0.15)	(0.15)
Organic N (g/ha)	SHR	127.3	4358.3	480.4	619.9	464.2	1901.3
	Conc. (mg/L)	(0.61)	(2.8)	(1.1)	(1.1)	(0.96)	(1.1)
	CON	135.2	235.3	12.4	47.1	107.6	2123.5
	Conc. (mg/L)	(1.4)	(1.5)	(0.37)	(0.43)	(1.4)	(1.3)
	CHP	54.8	671.8	72.0	201.6	88.5	1005.9
	Conc. (mg/L)	(0.41)	(0.64)	(0.37)	(0.42)	(0.37)	(0.56)
PO_4−P (g ha^{-1})	SHR	4.0	84.6	2.8	0.8	0.0	0.6
	Conc. (mg/L)	(0.03)	(0.05)	(0.01)	(0.01)	(0.000)	(0.001)
	CON	0.2	1.2	0.0	0.0	0.8	8.1
	Conc. (mg/L)	(0.001)	(0.01)	(0.0)	(0.0)	(0.012)	(0.01)
	CHP	3.7	1.3	5.0	1.4	0.5	0.5
	Conc. (mg/L)	(0.03)	(0.01)	(0.03)	(0.01)	(0.003)	(0.001)
Organic P (g ha^{-1})	SHR	11.3	273.9	38.6	49.0	38.4	160.0
	Conc. (mg/L)	(0.07)	(0.18)	(0.08)	(0.1)	(0.08)	(0.09)
	CON	10.4	18.5	1.0	3.8	8.6	173.6
	Conc. (mg/L)	(0.1)	(0.12)	(0.03)	(0.003)	(0.08)	(0.1)
	CHP	5.2	65.5	8.9	23.3	11.3	132.3
	Conc. (mg/L)	(0.04)	(0.06)	(0.05)	(0.05)	(0.05)	(0.07)

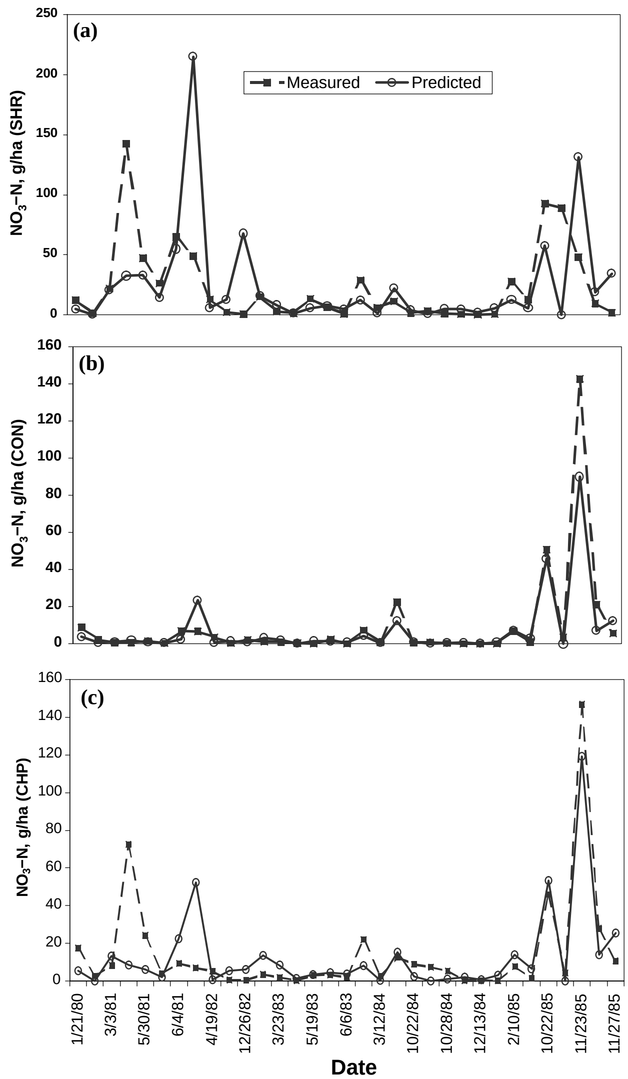

Figure 6. Simulated and measured NO_3−N runoff for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

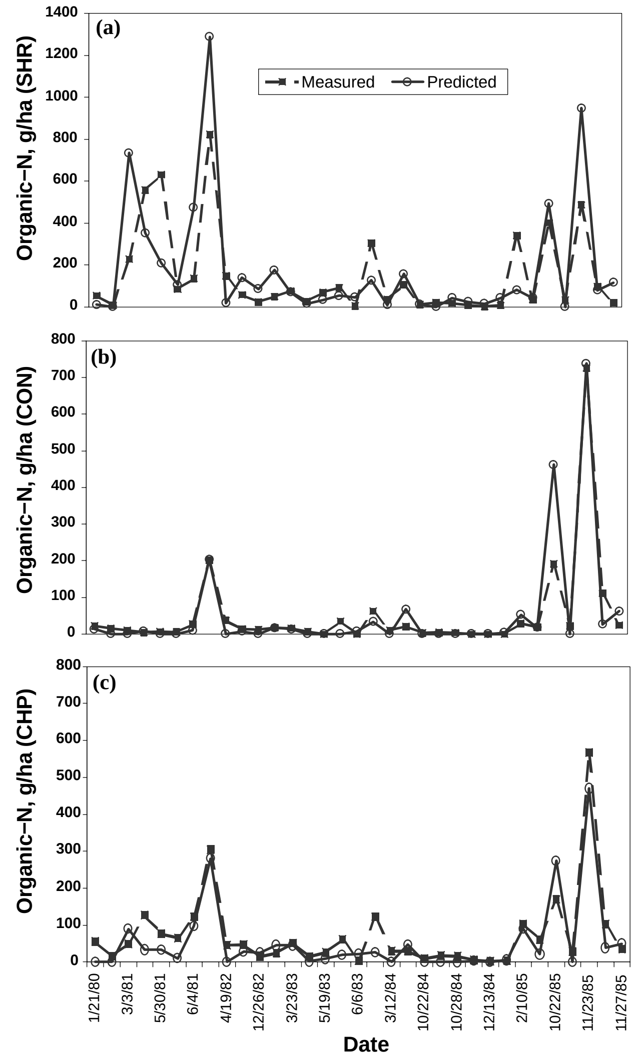

Figure 7. Simulated and measured organic N for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

concentrations losses continued to display less pronounced differences. By the fifth post−treatment year, revegetation was nearly complete; consequently, no significant differences were found among treatments.

NUTRIENTS

Nitrogen

The simulated average annual NO_3−N losses from all watersheds increased during the first post−treatment year (table 7 and fig. 6). However, the simulated NO_3−N concentration decreased for SHR and CHP watersheds and increased for the CON watersheds (table 7). Similar trends were indicated in the monitoring data (fig. 6). This NO_3−N response during the first post−treatment year is probably due to dilution of limited NO_3−N quantity in the watersheds resulting from higher runoff (because of increased rainfall) from 1980 to 1981. Note that in forested watersheds such as Alto, the magnitude of NO_3−N losses is in g/ha rather than kg/ha, as is usually observed on agricultural lands. Simulated organic N (sediment−attached nutrient) concentrations and losses increased considerably from 1980 to 1981 as a function of increased sediment losses.

During the second, third, and fourth post−treatment years, both NO_3−N and organic N losses for SHR and CHP watersheds were greater than for CON watersheds. However, the differences among watersheds continued to decrease each year. Because of higher simulated storm runoff during 1985, the simulated NO_3−N and organic N losses increased considerably from all watersheds. However, the NO_3−N and organic N concentrations did not differ much from concentrations of the previous year (1984). This similarity of concentrations in all treatments is attributed to the fact that the surface conditions in treated watersheds continued to become more stabilized due to vegetation after the 1982 post−treatment year.

As figures 6 and 7 show, the simulated and measured NO_3−N and organic N had similar trends during the six simulation years. These figures also show that the stabilization of the soil surface by simulating pasture crop and regrowth of the pine trees after the second post−treatment year reduced runoff relative to precipitation, and the concentration of sediment and nutrients it carries, a response that is also indicated in the monitoring data. Figure 8 indicates that the combined NO_3−N measured and simulated and organic N compare reasonably well. This could be due to

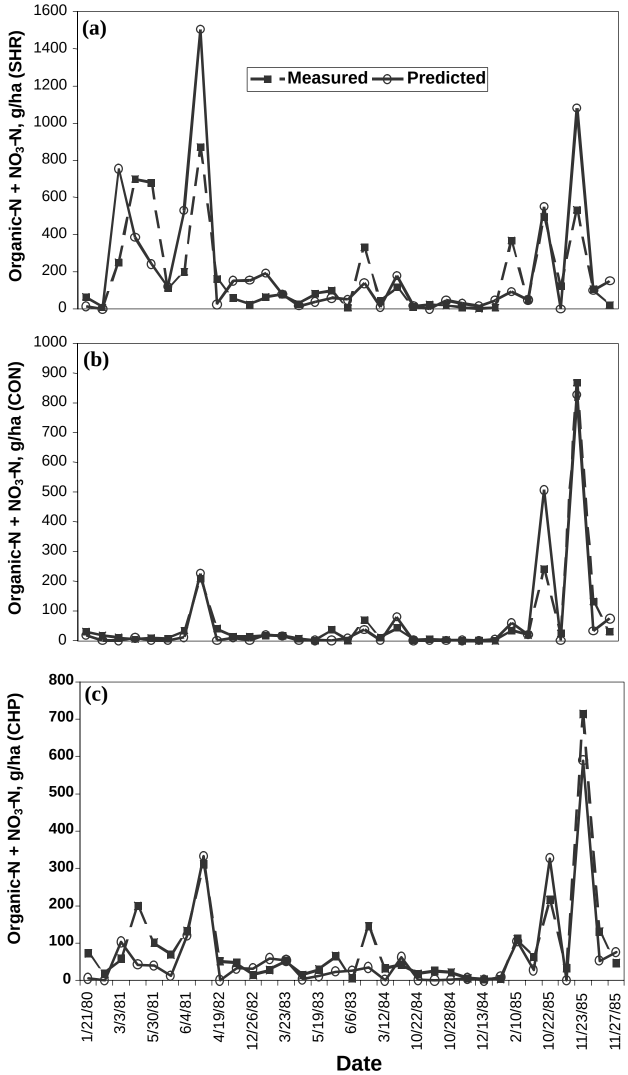

Figure 8. Simulated and measured NO_3-N + organic N for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

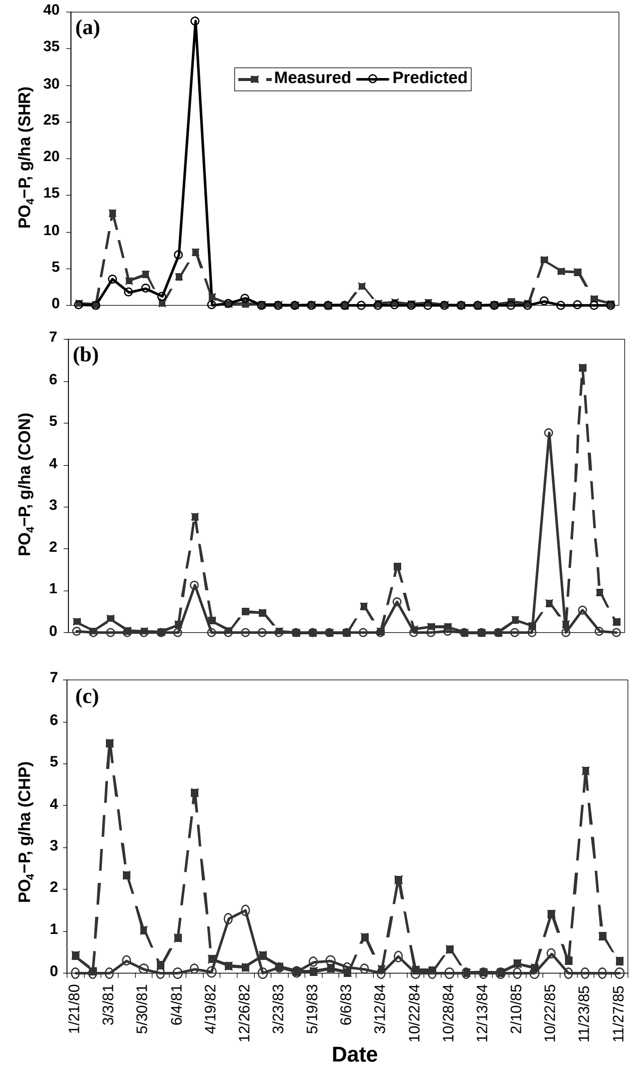

Figure 9. Simulated and measured PO_4-P for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

laboratory procedures of analyzing NO_3-N and organic N separately. The simulated NO_3-N plus organic N exhibited a better correlation with measured values as compared to results obtained from individual comparisons (table 5 and fig. 8).

Phosphorus

Although predicted and monitored PO_4-P losses were extremely low, APEX was able to predict an increase in simulated PO_4-P in SHR watersheds during the first post−treatment year (1981), which was also indicated in monitoring data. Because of soil surface revegetation after 1981, the difference among treatments was minimal (table 7 and fig. 9). Figure 9a shows higher PO_4-P losses from SHR watersheds than were measured during the field study. Nevertheless, it is important to note the low magnitude of simulated and measured PO_4-P losses (tables 5 and 9).

Due to dependency of organic P and organic N on sediment loss, the losses of organic P were similar to that of organic N; however, the magnitudes of the losses for organic P were much lower than those of organic N (table 7 and fig. 10). Figure 10 shows the similarity of trends by measured and predicted organic P during the simulation period. However, as is demonstrated in table 5 and figure 11, the measured and simulated PO_4-P plus organic P (total P) showed good agreement. Similar to nitrogen, this could be due to laboratory analysis of PO_4-P and organic P separately. In addition, the simulated average total P had a better correlation with measured values as compared with individual comparisons (table 5 and fig. 11).

Effect of SMZs and Roads on Flow and Sediment Loss

Table 8 shows the effect of SMZs on simulated average annual runoff and sediment loss from forested land. With the filter flow fraction increased up to 0.25, the average annual runoff decreased about 20%. However, average annual flow was not affected by filter flow fractions greater than 0.25. The results indicate that SMZs can effectively reduce sediment loss from a cleaned and replanted area, but effectiveness is monotonically related to the fraction of runoff that occurs as sheet flow and not as concentrated flow. The reduction of the simulated average sediment loss from forested land by SMZs is also shown in table 8. With the filter flow fraction increased from 0.0 to 0.95, the average annual sediment loss decreased

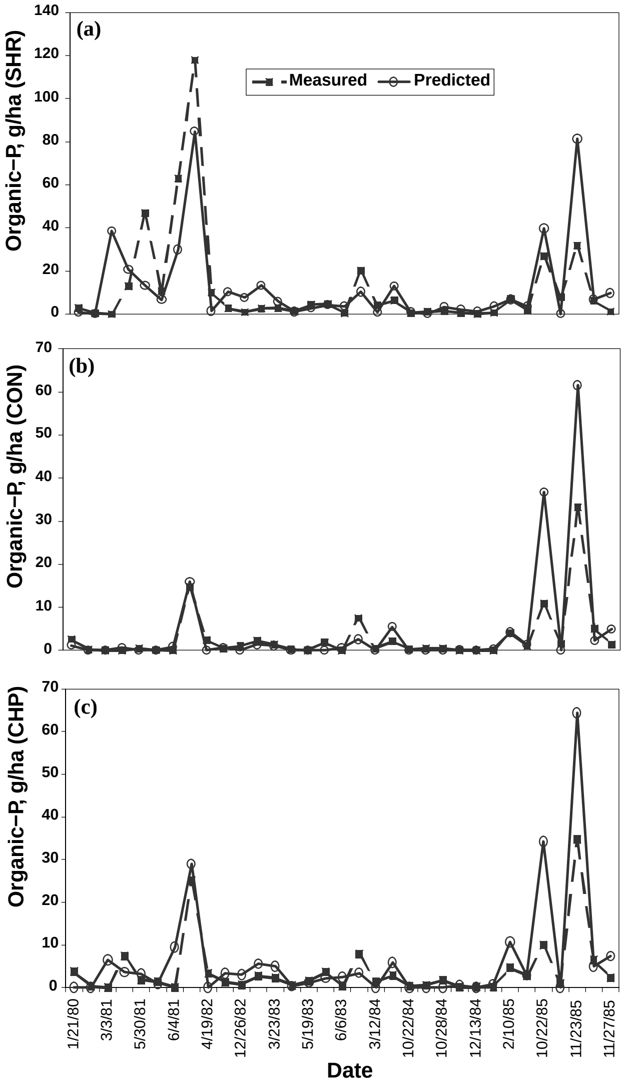

Figure 10. Simulated and measured organic P for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

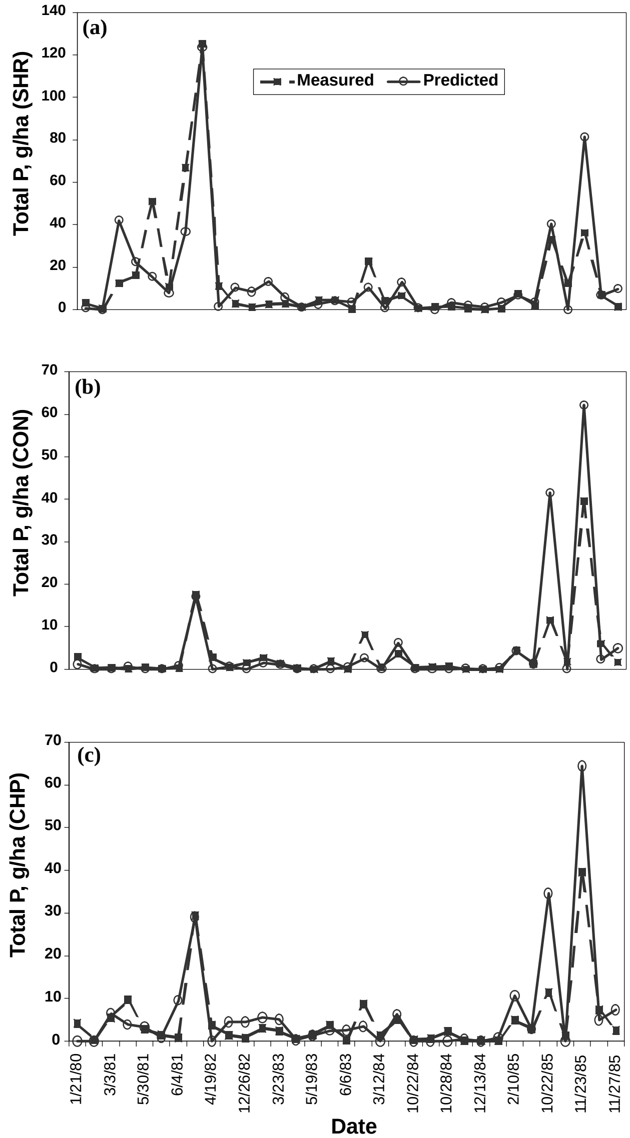

Figure 11. Simulated and measured PO_4−P + organic P for (a) SHR, (b) CON, and (c) CHP treatments during 1980−1985 (average of three replications).

about 75%. This demonstrates the importance of SMZs on sediment reduction in forested land.

The average annual flow increased with higher road density. For example, the simulated road density of 3 km/km^2 with a slope of 1% resulted in 565 mm of runoff from roads and a 59% increase in average annual runoff from the watershed (table 9). The runoff increase became more pronounced with an increase in road slope. Table 9 shows that the runoff from roads in the above example increased from 565 to 666 mm, while runoff from the watershed increased from 27.3 to 29.1 mm, with an increase in road slope from 1% to 15%. The simulated annual average sediment loss increased noticeably with higher road density. For instance, the simulated road density of 3 km/km^2 with slope of 1% resulted in 32.5 t/ha of sediment loss from roads, which is a 3.5 times increase in average annual sediment loss from the watershed compared to the simulation without roads (table 9). The increase in sediment loss became more pronounced with an increase in road slopes (table 9). For example, the sediment loss from roads at a density of 3 km/km^2 increased from 32.5 to 853.6 t/ha with an increase in road slope from 1% to 15%. At the same road density, watershed sediment loss increased from 0.46 to 3.65 t/ha with an increase in slope from 1% to 15%.

Table 8. Simulated effect of SMZs in controlling runoff and sediment losses.

Filter Flow Fraction	Average Annual Flow (mm)	Average Annual Sediment Loss (t/ha)
0.00	120	0.61
0.10	101	0.52
0.25	97	0.42
0.50	97	0.30
0.75	97	0.20
0.95	97	0.15

SUMMARY AND CONCLUSION

The effects of silvicultural practices on stream runoff and loading of sediments and nutrients were examined using an enhanced APEX model with several adaptations to allow better simulation capabilities for forestry. Historical data from Alto, Texas, were used to verify the modified APEX for forestry. The data from Alto included measured storm runoff, sediment, and nutrients from nine small (2.6 to 2.8 ha) watersheds with three replicates of each of the following

Table 9. Simulated average annual runoff and sediment losses for roads within given density and slope ranges.

Road Density (km/km^2)	Road Slope (%)	Runoff		Sediment Loss	
		Road (mm)	Watershed (mm)	Road (t/ha)	Watershed (t/ha)
1	1	565	20.6	26.7	0.19
2	1	565	23.9	30.5	0.31
3	1	565	27.3	32.5	0.46
1	5	613	20.9	77.9	0.26
2	5	613	24.5	99.1	0.53
3	5	613	28.1	110.4	0.89
1	10	348	21.1	159.6	0.36
2	10	348	24.9	208.5	0.84
3	10	348	28.8	263.4	1.65
1	15	666	21.2	333.7	0.58
2	15	666	25.2	852.3	1.74
3	15	666	29.1	853.6	3.65

treatments (1) clearing, shearing, windrowing, and burning (SHR); (2) clearcutting, roller chopping, and burning (CHP); and (3) undisturbed control (CON). Modifications that were made to APEX to better describe the forestry conditions included: rainfall interception by canopy, surface litter water balance, quick return flow, soluble P upward movement by evaporation, new nutrient enrichment ratio parameters, and partial burning of aboveground plant material.

The simulations of the Alto watersheds covered a 37−year period beginning with conditions in 1948 when pine trees were planted in those watersheds. Curve numbers (CN2) were adjusted for the six harvested watersheds to describe the SHR and CHP treatments during 1980−1985. The predicted and measured average runoff and sediment and nutrient losses per storm event were sufficiently close to provide indications that APEX was capturing the major hydrologic processes. Similar trends were also obtained between measured and predicted storm runoff and sediment and nutrient losses throughout the simulation period.

Because of more soil surface exposure and loss of ground cover due to the treatments, simulated and measured storm runoff and loadings of sediments and nutrients from SHR and CHP watersheds greatly increased during the first post−treatment year. In subsequent post−treatment years, the simulation of surface revegetation (as pasture) in SHR and CHP watersheds resulted in increasing reductions of simulated sediment and nutrient losses and greater simulations of values compared to the control watershed. A similar pattern was observed in the historical data. In general, simulated storm runoff from SHR and CHP watersheds were higher than from CON watersheds during the five post−treatment years. However, surface revegetation after the first post−treatment year narrowed the differences in treatment responses in a similar manner to that observed in the historical data.

The APEX simulation of SMZs showed a decrease in both runoff and sediment loss, although effectiveness in sediment removal increases with the fraction of runoff entering the SMZs as sheet flow. Forest roads increased flow and sediment loss noticeably. The increase in runoff and sediment loss became more pronounced, as expected, with greater slope and density of roads.

The modified APEX model was capable of simulating a variety of forest conditions from planting to harvesting, site preparation (shear and windrow and chopped), and regrowth. The model performance is reasonable, given the difficulties associated with field measurements and model simulations, and provides the basis for a planned second phase of this study that will describe the fate and transport of herbicides under forestry conditions. In addition, since the comparison of measured and simulated values from the modified APEX was done without any calibration, further refinement of some parameters within the model might be needed to improve the simulation results.

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